In-source laser spectroscopy of Polonium
Probing the nuclear structure accross Z=82 with mean-squared charge radii

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Outline

- General physics interest
  - Interests around the Z=82 shell closure
  - Alpha decay and in-beam studies
  - Ground- and isomer-state properties of polonium
- In-source laser spectroscopy with ISOLDE-RILIS
  - Technique
  - Laser ionisation of polonium

The Shell Model

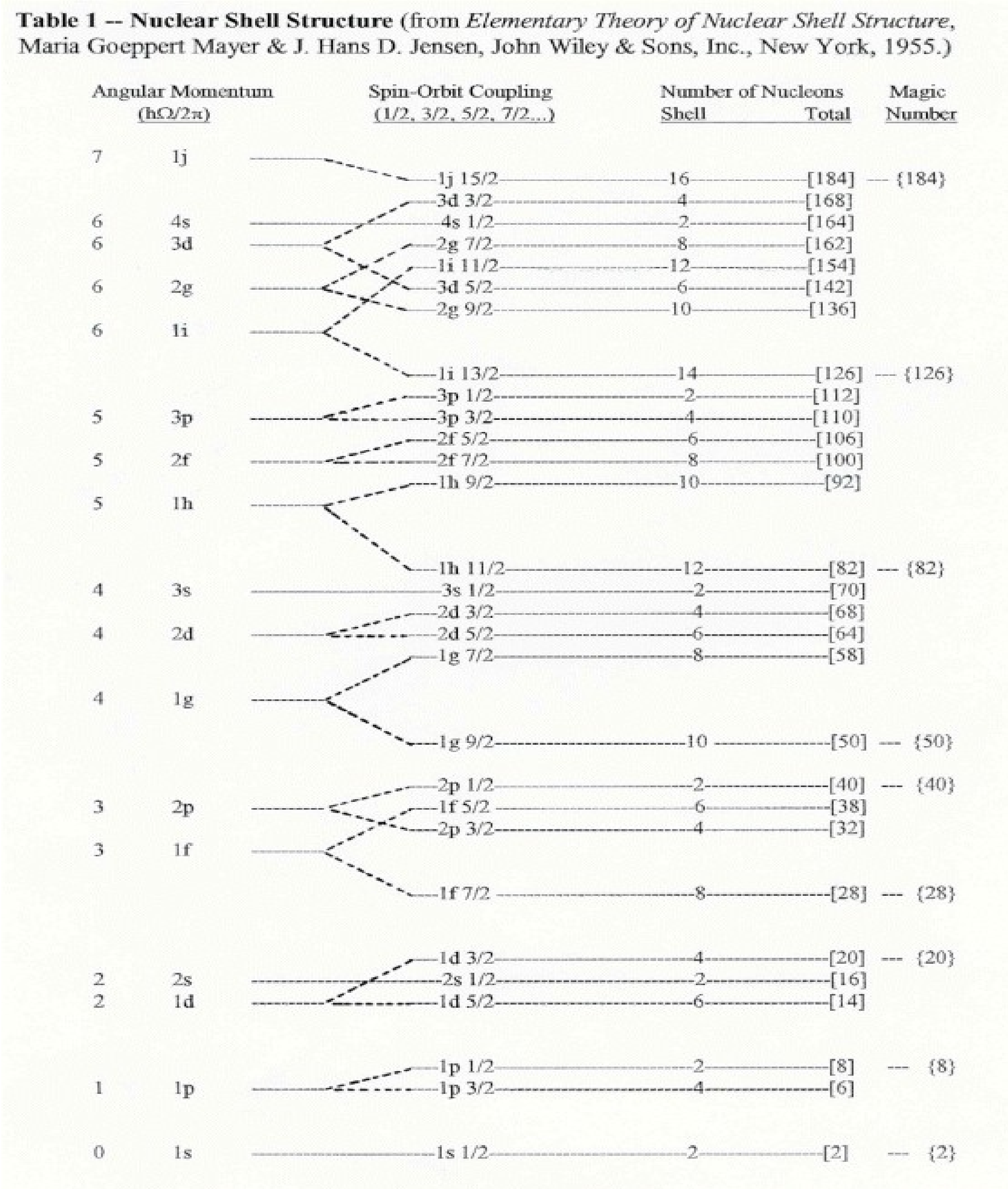
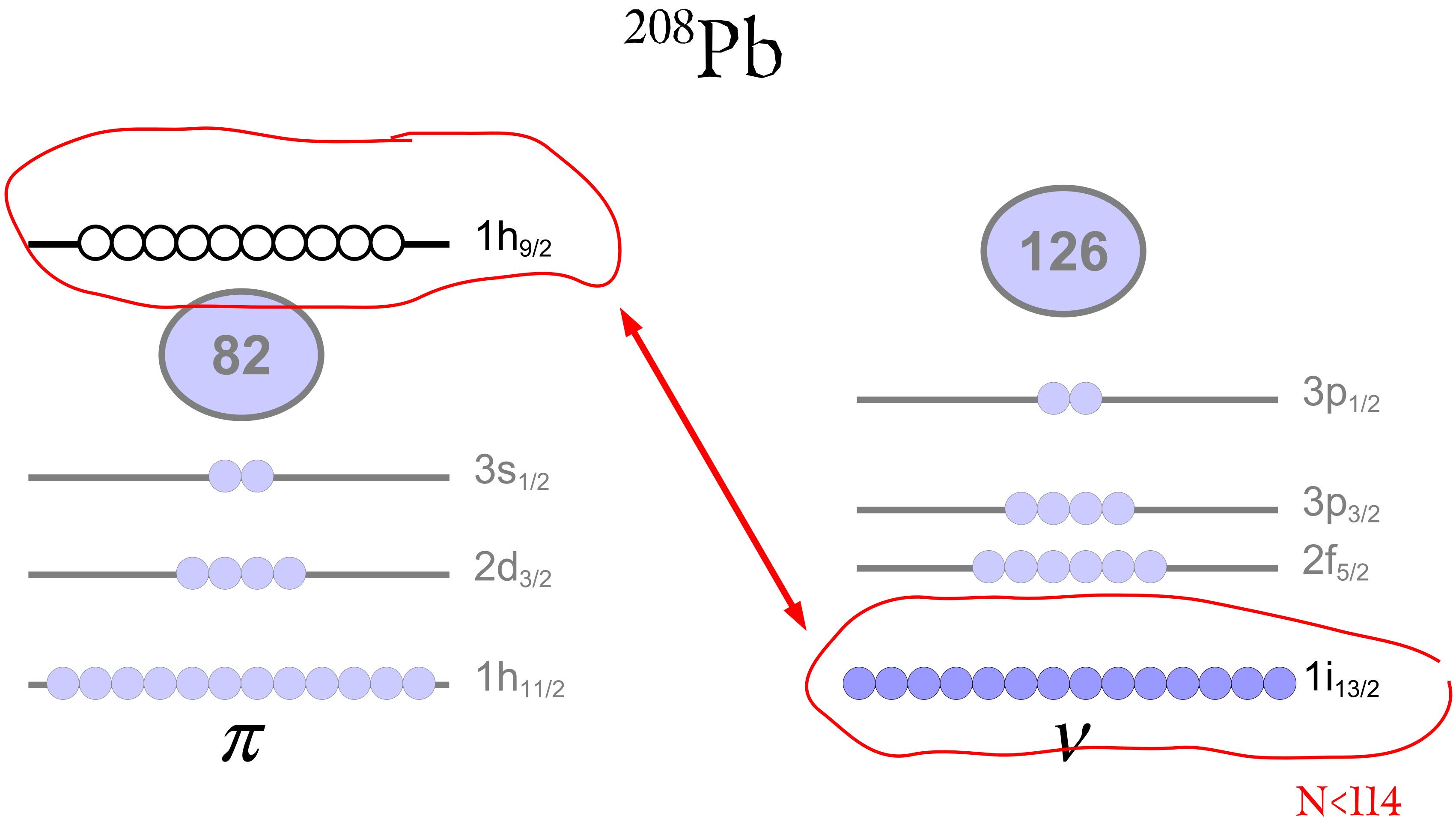
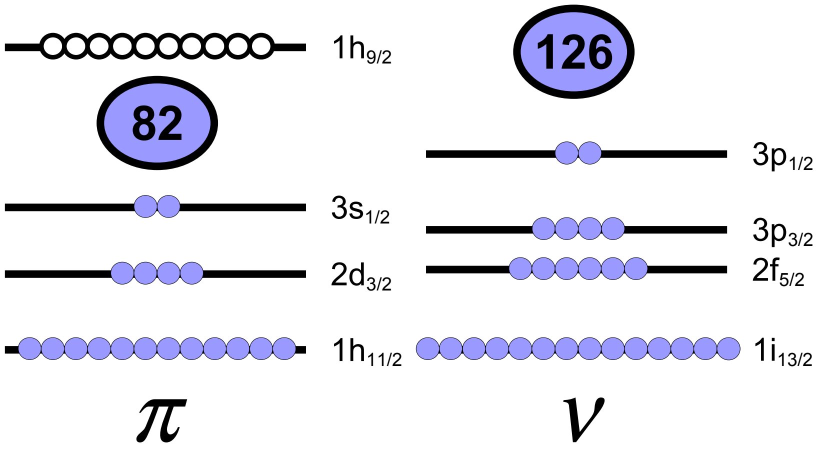


Table 1 -- Nuclear Shell Structure (from *Elementary Theory of Nuclear Shell Structure*, Maria Goeppert Mayer & J. Hans D. Jensen, John Wiley & Sons, Inc., New York, 1955.)

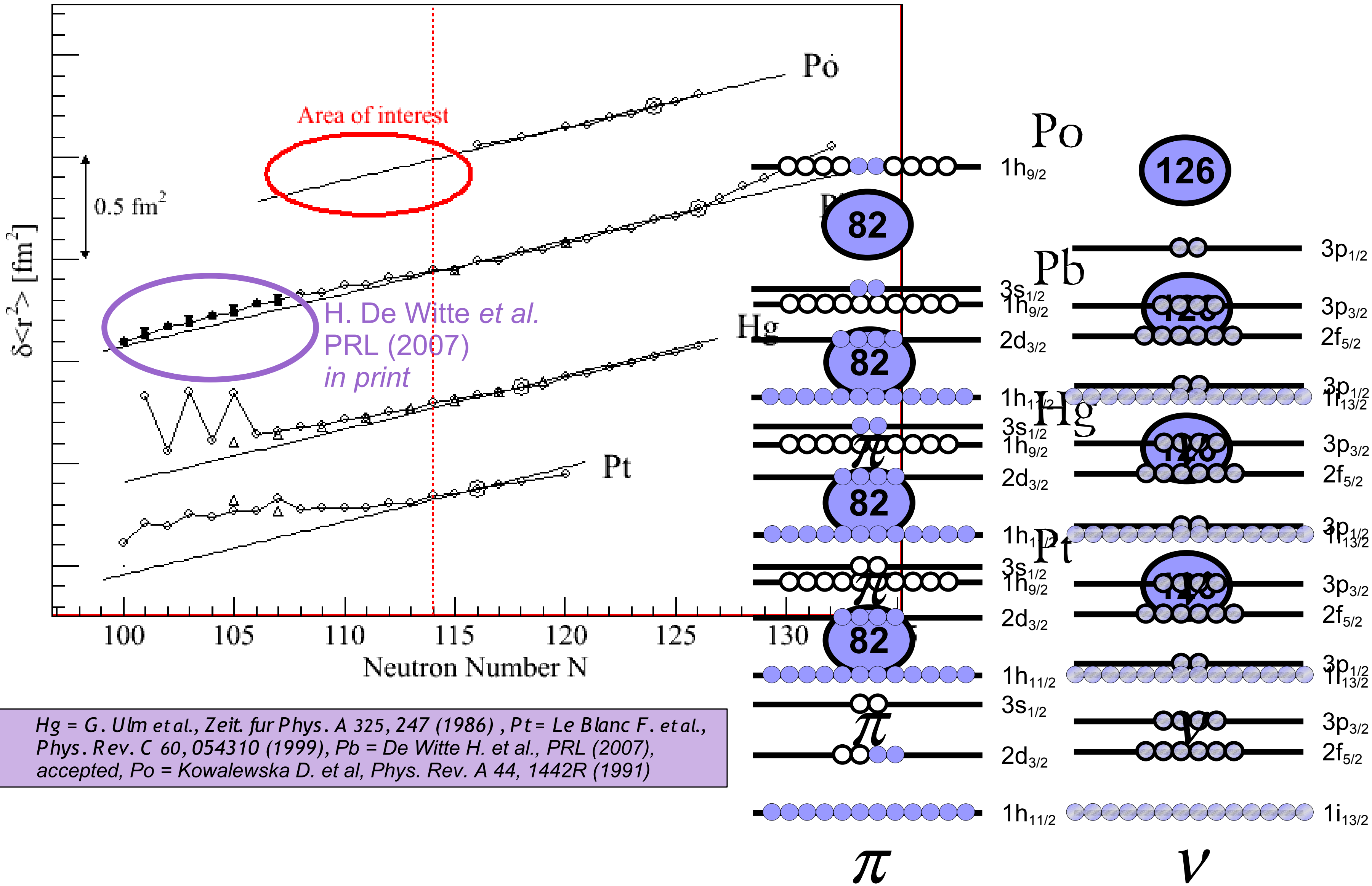
Angular Momentum ($h\Omega/2\pi$)		Spin-Orbit Coupling (1/2, 3/2, 5/2, 7/2,...)	Number of Nucleons Shell	Total	Magic Number
7	1j				
		1j 15/2	16	[184]	{184}
		3d 3/2	4	[168]	
6	4s	4s 1/2	2	[164]	
6	3d	2g 7/2	8	[162]	
		1i 11/2	12	[154]	
6	2g	3d 5/2	6	[142]	
		2g 9/2	10	[136]	
6	1i				
		1i 13/2	14	[126]	{126}
		3p 1/2	2	[112]	
5	3p	3p 3/2	4	[110]	
		2f 5/2	6	[106]	
5	2f	2f 7/2	8	[100]	
		1h 9/2	10	[92]	
5	1h				
		1h 11/2	12	[82]	{82}
4	3s	3s 1/2	2	[70]	
		2d 3/2	4	[68]	
4	2d	2d 5/2	6	[64]	
		1g 7/2	8	[58]	
4	1g				
		1g 9/2	10	[50]	{50}
		2p 1/2	2	[40]	{40}
3	2p	1f 5/2	6	[38]	
		2p 3/2	4	[32]	
3	1f				
		1f 7/2	8	[28]	{28}
		1d 3/2	4	[20]	{20}
2	2s	2s 1/2	2	[16]	
2	1d	1d 5/2	6	[14]	
		1p 1/2	2	[8]	{8}
1	1p	1p 3/2	4	[6]	
0	1s	1s 1/2	2	[2]	{2}

Shell model around Z=82



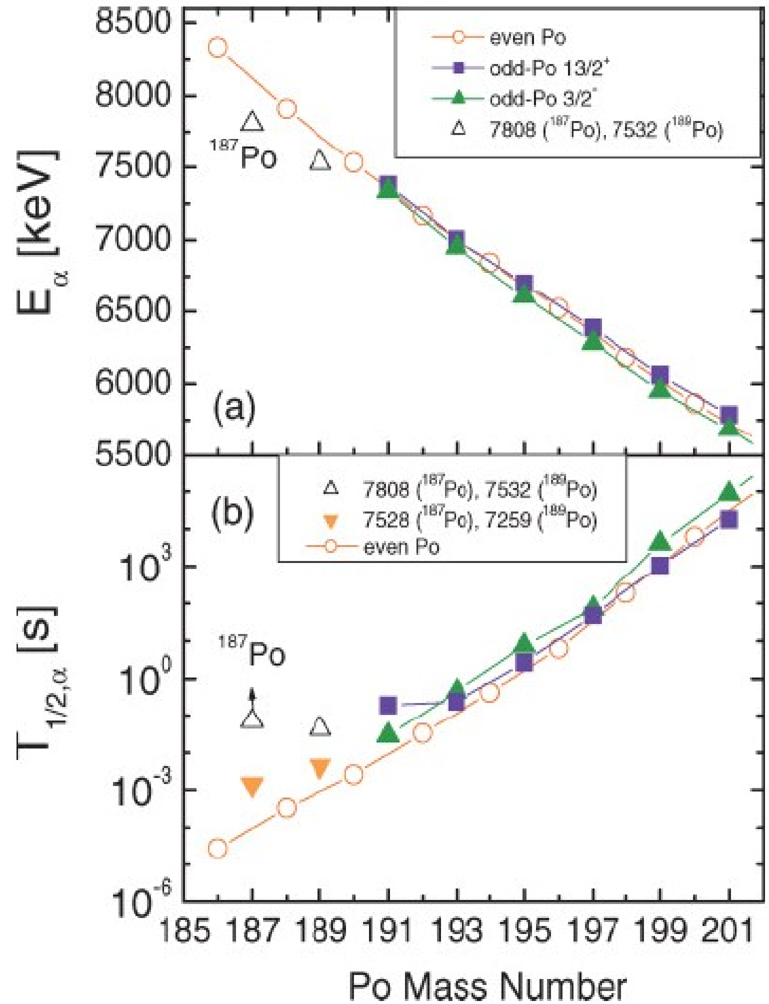

1h9/2
82
3s1/2
2d3/2
1h11/2
126
3p1/2
3p3/2
2f5/2
1i13/2
π
ν

$\delta\langle r^2\rangle$ around Z=82



Hg = G. Ulm et al., Zeit. fur Phys. A 325, 247 (1986) , Pt = Le Blanc F. et al., Phys. Rev. C 60, 054310 (1999), Pb = De Witte H. et al., PRL (2007), accepted, Po = Kowalewska D. et al, Phys. Rev. A 44, 1442R (1991)

- Smooth dependence of the alpha energies and partial half-lives
- First major discrepancy at ^{191m}Po: onset of oblate deformation
- ^{187}Po & ^{189}Po: prolate configurations
- The even isotopes remain on the smooth trend...
- Isomerically purified beams could reveal new information with unhindered decays (^{193,195,197}Po)



A.N. Andreyev et al., PRC 73, p.044324, (2006)

Odd isotope nuclear spectroscopy

More precise conversion coefficients in intruder states in Pb

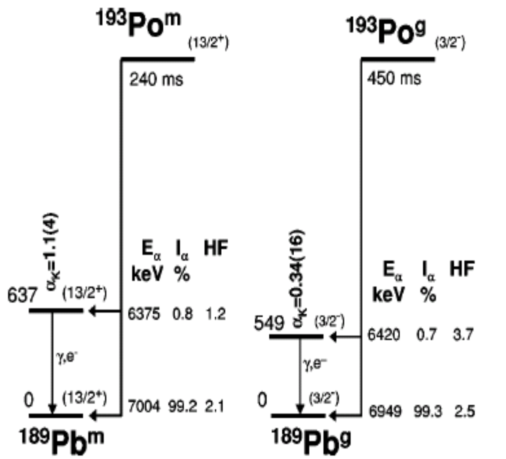


FIG. 2. Alpha-decay scheme of ^{193m,g}Po. Indicated are α-particle energies, intensities, and hindrance factor values (see Sec. III). Spin and parity assignments are discussed further in the text.

K. Van de Vel et al., PRC 65, p.064301, (2002)

=> E0-M1-E2 transition strength

Mass derivation <= from Pb mass and Po Q_a value

Identification of cross-over decays in ^{193,195,197}Po

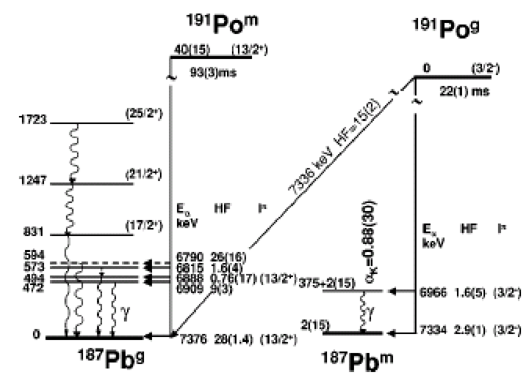


FIG. 3. Alpha-decay scheme of ^{191m,g}Po. For α decays the energies (in keV) and hindrance factors are given. The indicated spin and parity assignments are the values deduced from our analysis. The crossover transition from the low-spin isomer in ^{191}Po to the high-spin isomer in ^{187}Pb is indicated by the slope line. The tentatively identified α decay at 6790 keV and the state at 594 keV are shown by the dashed lines. See main text and Table I for details.

A.N. Andreyev et al., PRC 66, p.014313, (2002)

\+ identification of new highly non-yrast levels in ^{189,191,193}Pb
\+ study of isomerically separated beams

Some of these studies can be performed parasitically of the HFS measurements *(α–γ studies)* but some others require full intensity for good statistics *(cross-over decays)*

In-Beam studies

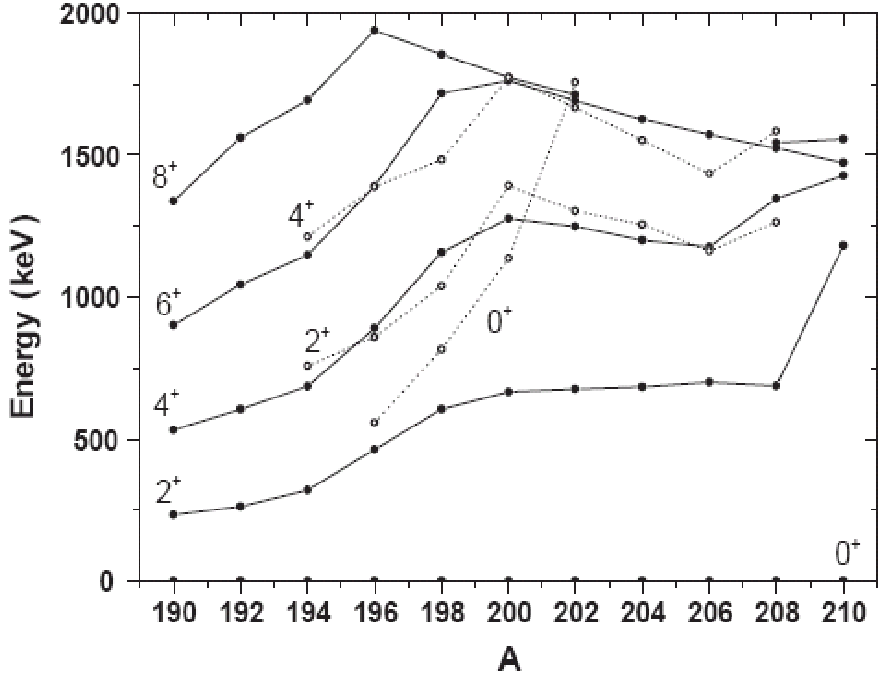
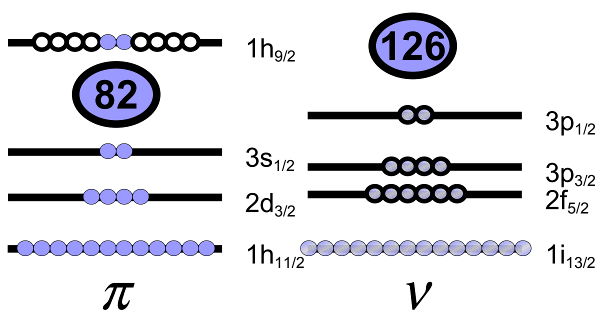


Fig. 4. Systematics of selected positive-parity near-yrast states for even-even polonium isotopes. Yrast states are indicated by filled circles, states with the same spin and parity are connected by a full line. The non-yrast levels, indicated with empty circles, are connected with a dotted line.

K. Van de Vel, EPJA 17, p.167-171 (2003)

- Constant energy of the yrast states between ^{208}Po and ^{200}Po well described by PCM ($2\pi\oplus$Pb (vibrating core))
- Model fails to describe energy levels for A<198 without unphysical interaction between the valence protons and the lead core.
- Failure in explaining the 0_2^+ state behaviour as well

=> configuration mixing

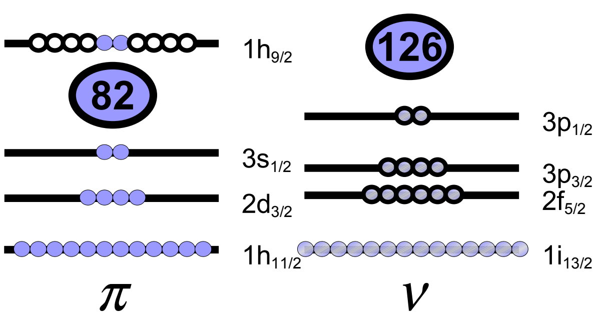


- Weak coupling of the $i_{13/2}$ valence neutron with the even Po core results in similar trends between even isotope energy levels and neighbouring odd isotope energy levels
- Unfavoured $15/2^+$, $19/2^+$ and $23/2^+$ in odd $^{191-195}Po$

  => oblate deformation

- Rise in energy of favoured levels at ^{191}Po

  => change in interaction, ie in configuration of the core



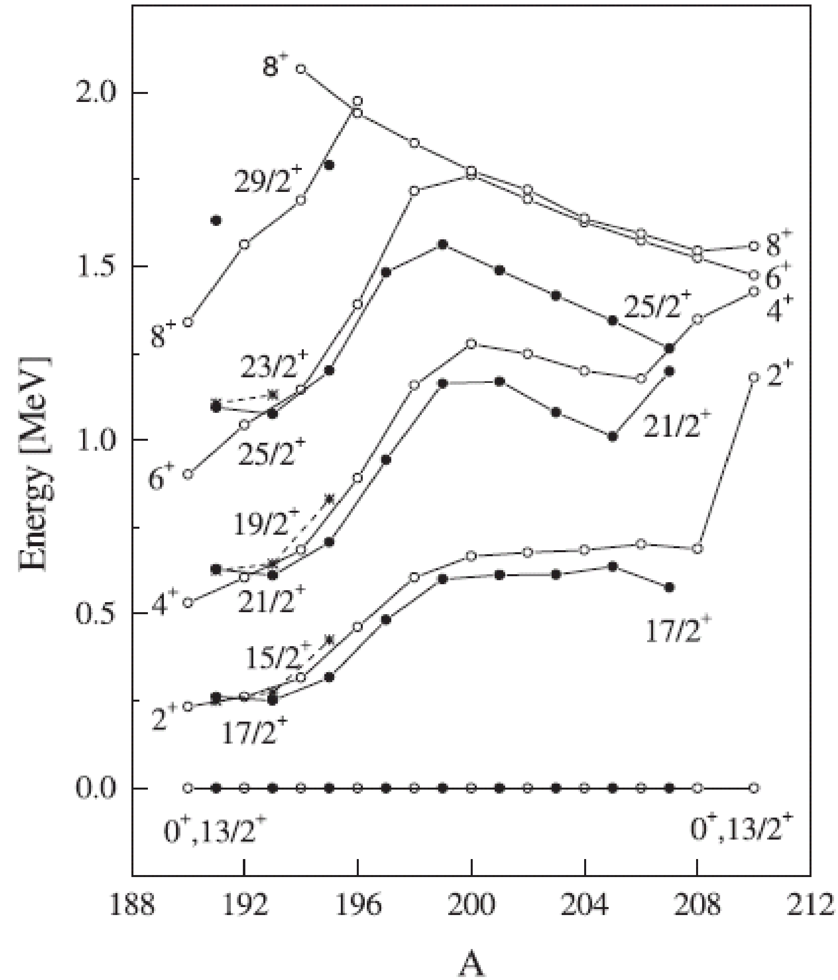
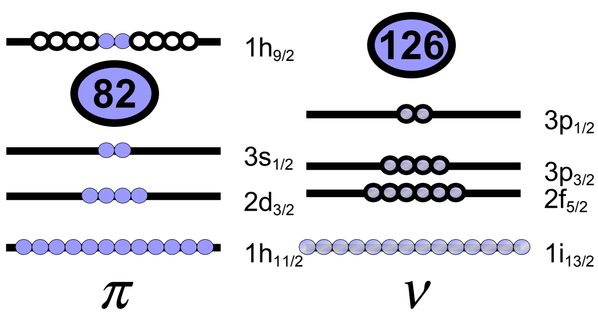


Figure 27. Energies of the yrast levels of the even-mass $^{190-210}Po$ nuclei (open circles) together with the levels on top of the $13/2^+$ states in the odd-mass $^{191-207}Po$ nuclei; full circles denote the favoured states and the asterisks the unfavoured ones.

R. Julin, K. Helariutta and M. Muikku, JPG 27, R109-R139 (2001)

Ground-State Properties

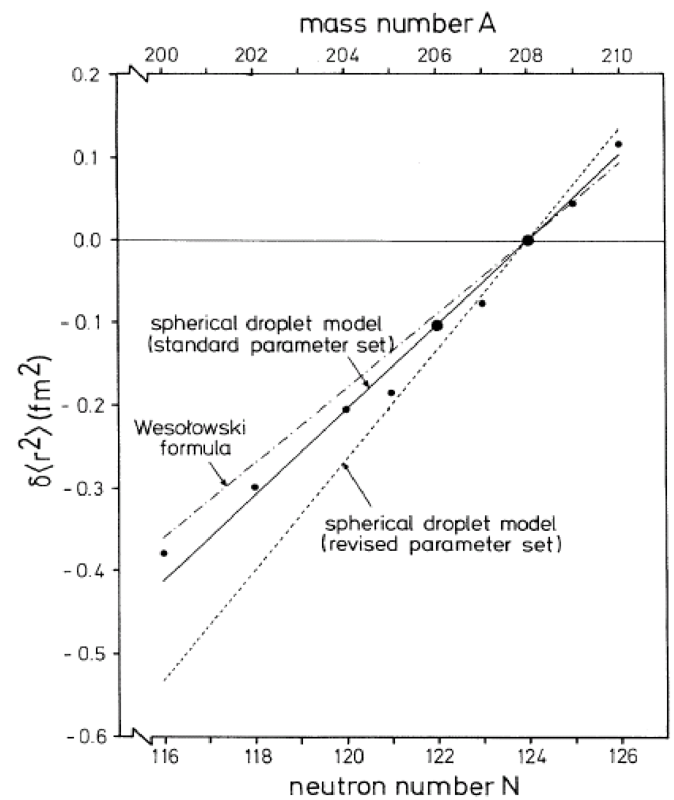
- Ground-state properties are model independent observables
- $\delta\langle r^2\rangle$ offers a direct observation of the nuclear shape
- Very sensitive probe of key parameters in MF *(determining the strength of the pairing)*
- Knowledge is limited to around N=126
- Polonium is a radioactive element



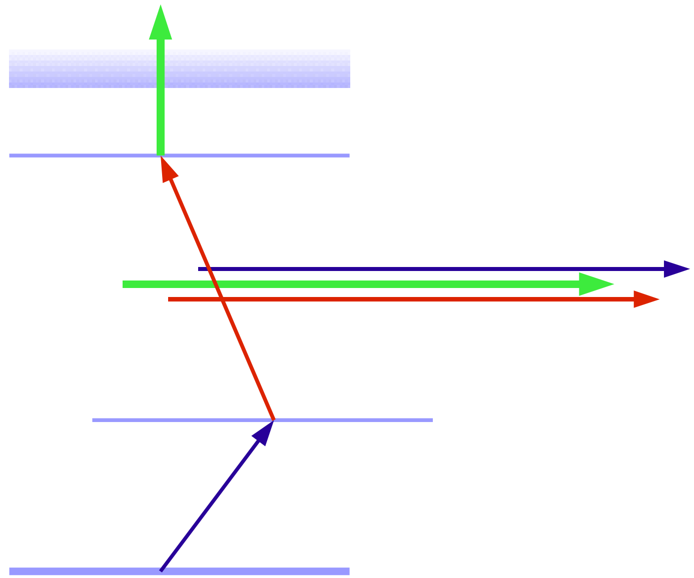
Hyperfine-structure constants of the $6p^3 7s\ ^5S_2$ level in Po I and nuclear moments of odd-mass Po isotopes.

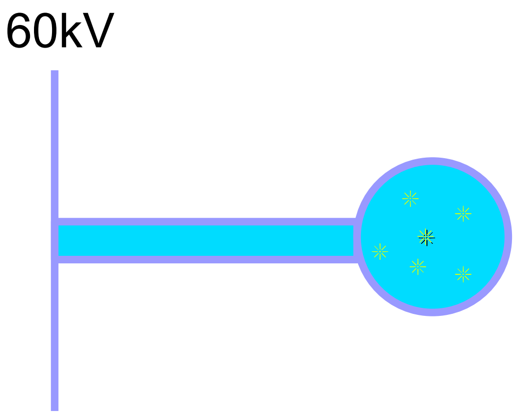
Mass number	A (MHz)	B (MHz)	μ_I (μ_N)	Q (b)
209	2127(3)	0	0.606(45)	0
207	564(1)	367(7)	0.793(55)	0.28
205	542(2)	241(13)	0.760(55)	0.17

D. Kowalewska et al., PRA 44, R1442-R1445 (1991)



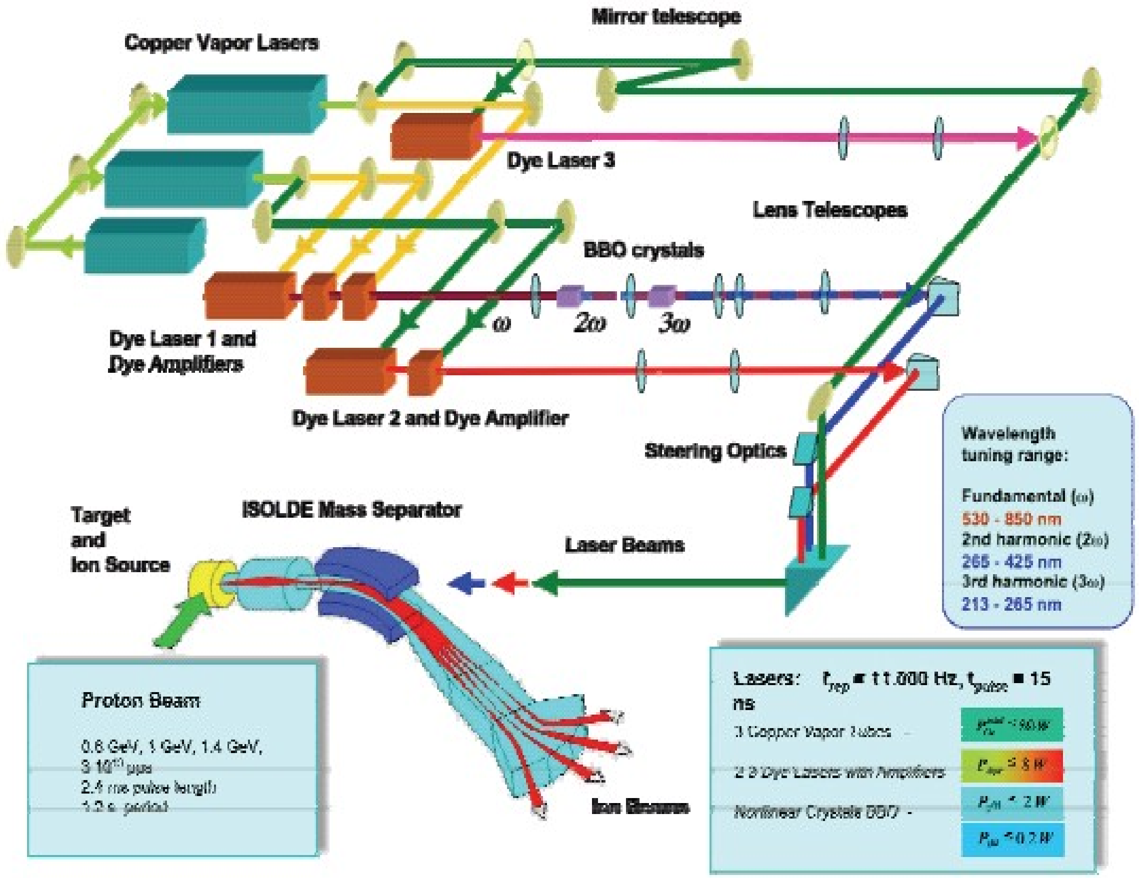
Laser ion sources



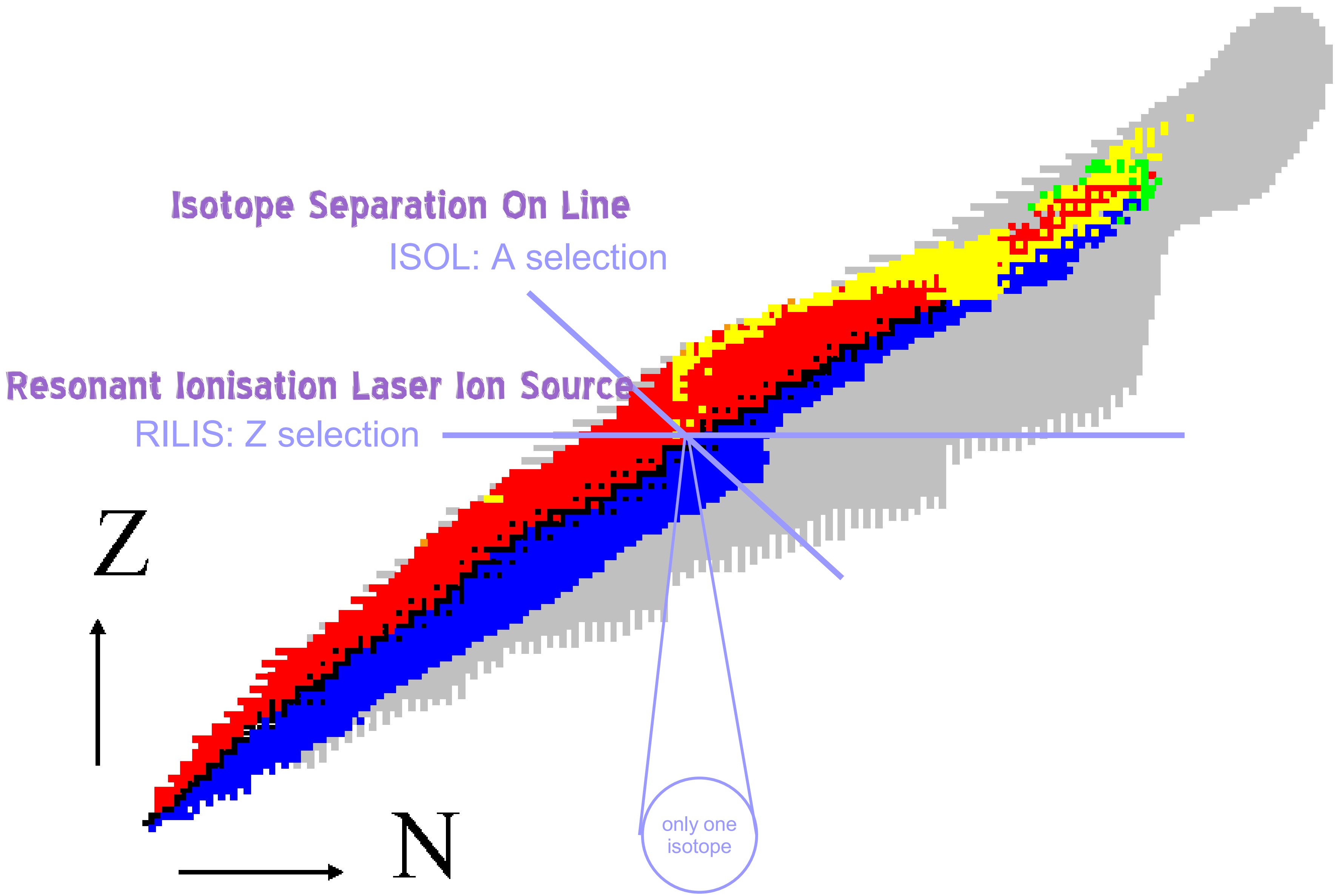


- Atom source (hot cavity)
- Transfer tube where the ions meet the lasers
- Acceleration electrode
- Lasers on the proper frequencies and the proper timing

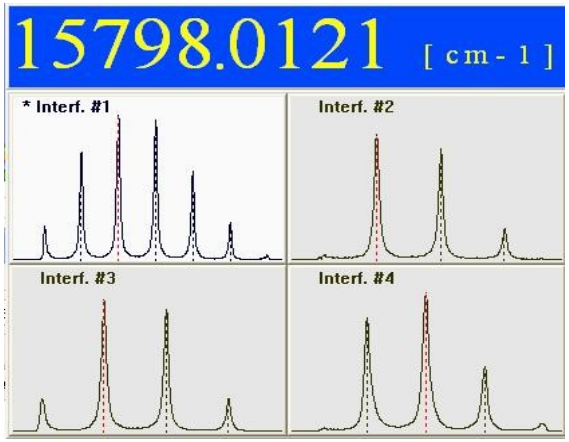
ISOLDE RILIS

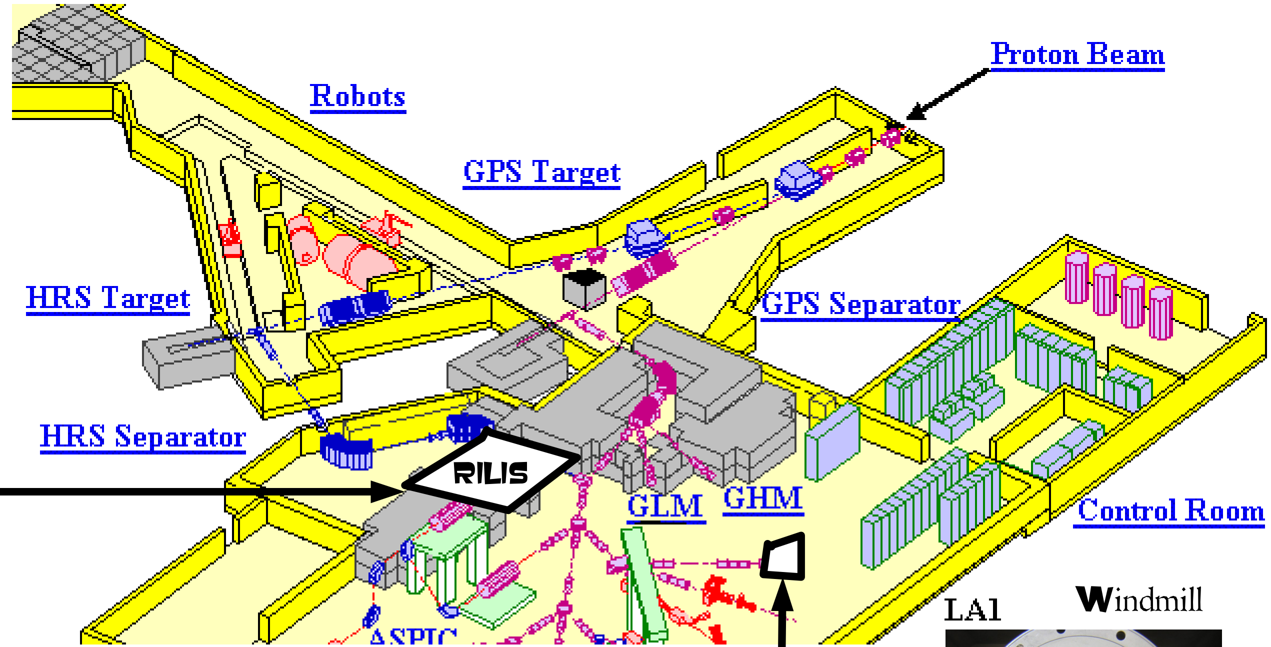


Bruce Marsh, The ISOLDE RILIS, Poznan LASER workshop 2006

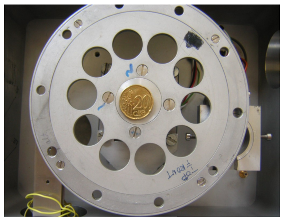

Isotope Separation On Line
ISOL: A selection
Resonant Ionisation Laser Ion Source
RILIS: Z selection
Z
N
only one isotope

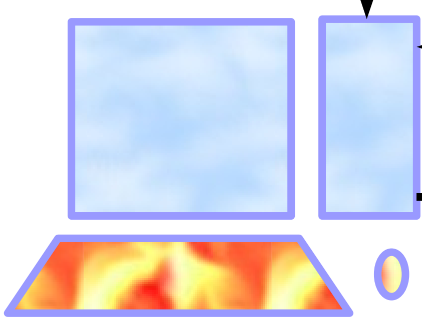
Experimental Layout

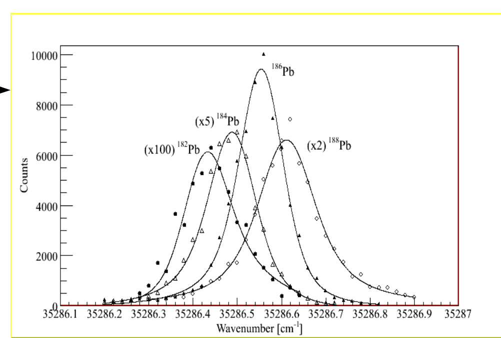




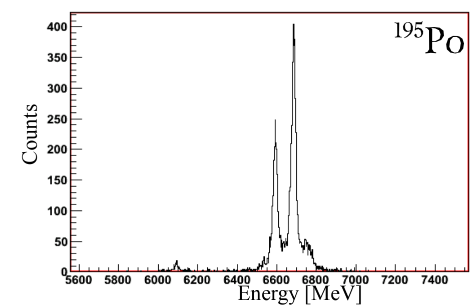
LA1 Windmill



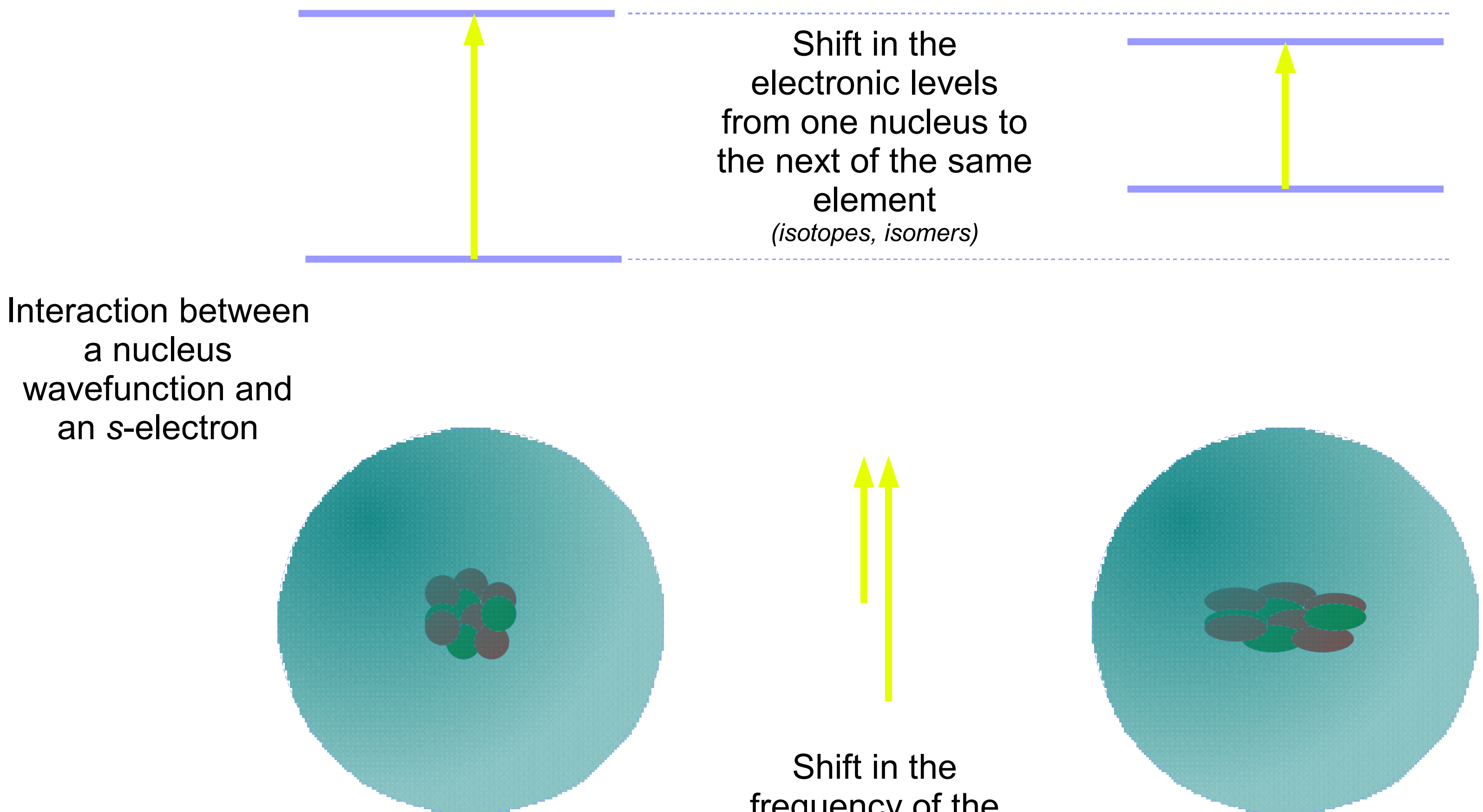




H. De Witte et al., PRL (2007) in print

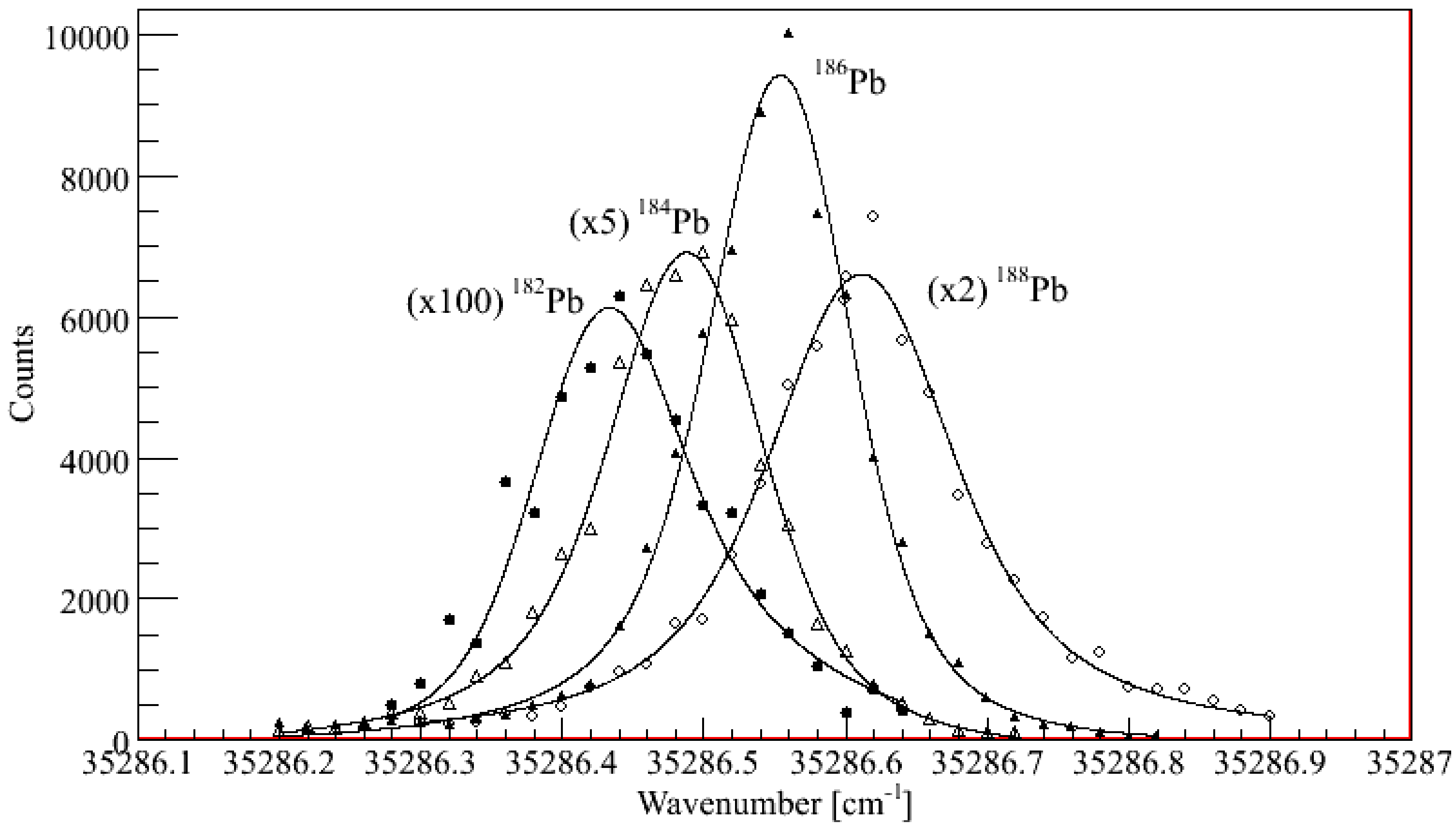


Isotope Shift



$$\Delta\nu \approx F \cdot \delta\langle r^2 \rangle + Mass\ Shift$$

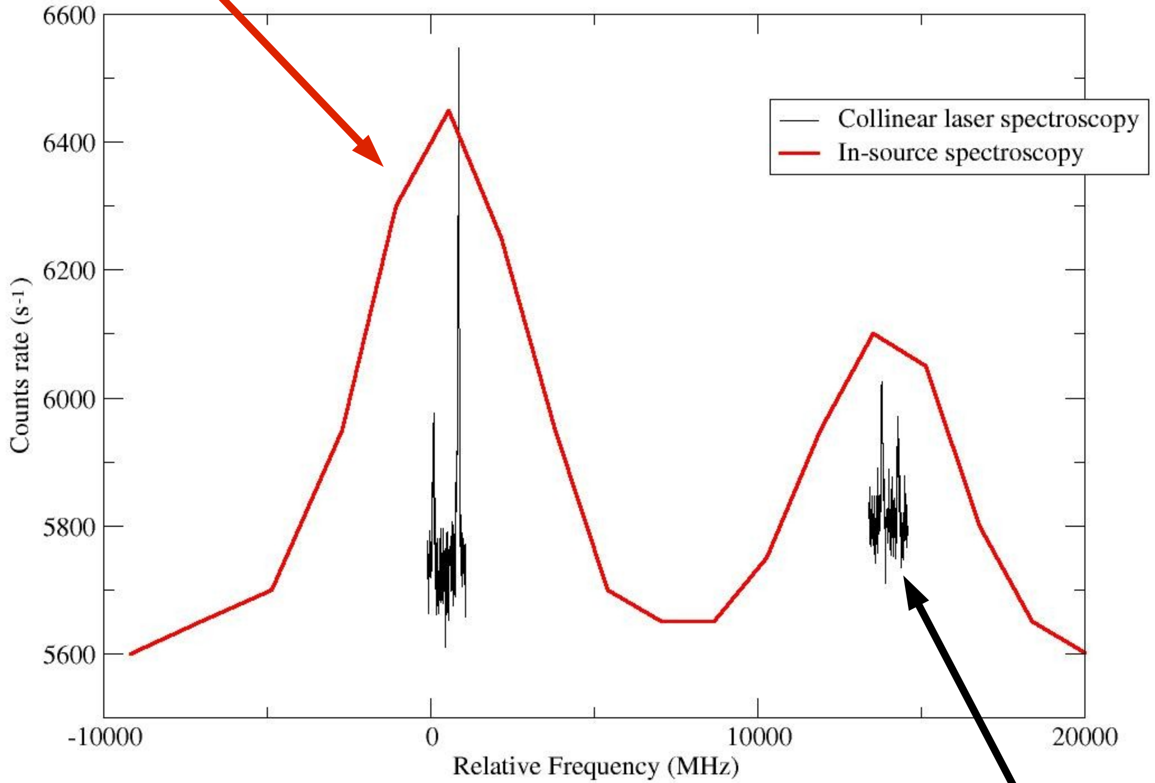
Isotope shift: an example



H. De Witte et al., PRL (2007) in print

Atomic Spectroscopy

Doppler broaden sample from a hot source results in wide spectra



Doppler compressed sample from an accelerated beam results in narrow, almost Doppler-free spectra

K. Flanagan, INTC presentation (2007)

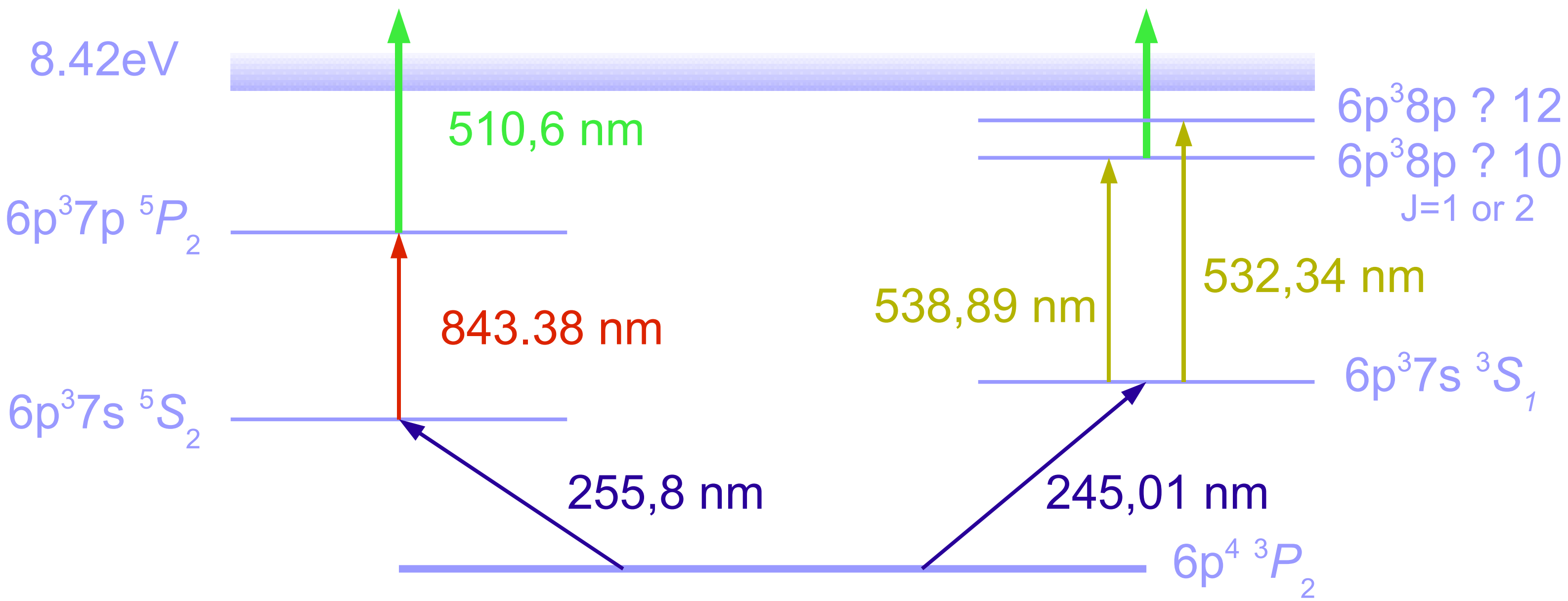
Atomic Spectroscopy

- In flight spectroscopy
  - + Doppler compression of fast-beam *(improved resolution)*
  - - Creation of the beam *(external ion source)*
  - - Manipulation for detection *(neutralisation, polarisation, fluorescence, ...)*
  - - High yield required *(or work with additional equipment such as an RFQ cooler)*

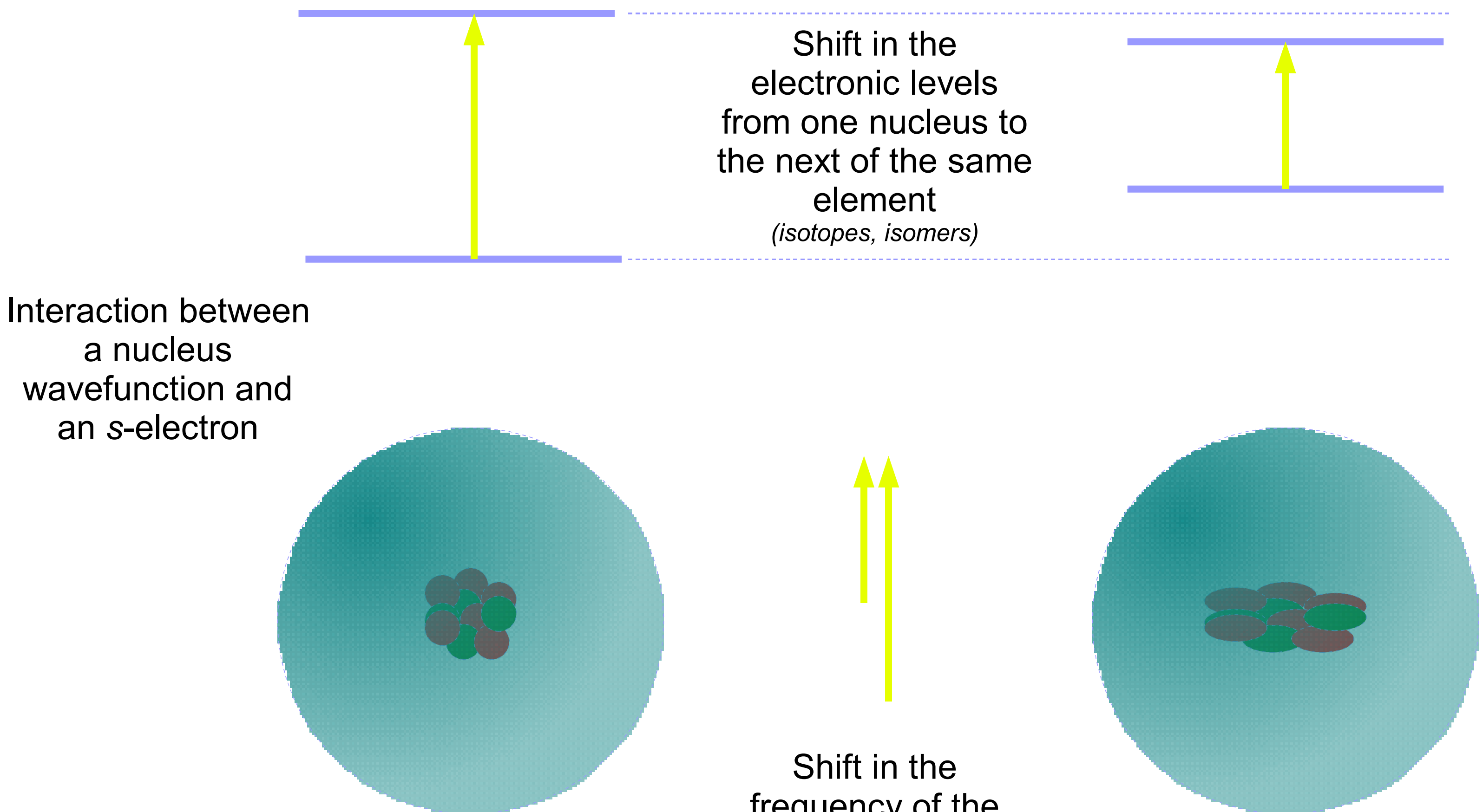
Appropriate for heavy elements
Po detection by α-decay

- In source spectroscopy
  - - Doppler broadened sample *(thermal distribution of the source)*
  - + No need to create a beam *(spectroscopy is the source)*
  - + Simple detection of the flux of ions *(beam current, nuclear spectroscopy,...)*
  - + Sensitive to extremely low yields *(few ions per second for ^{182}Pb)*

Po excitation schemes

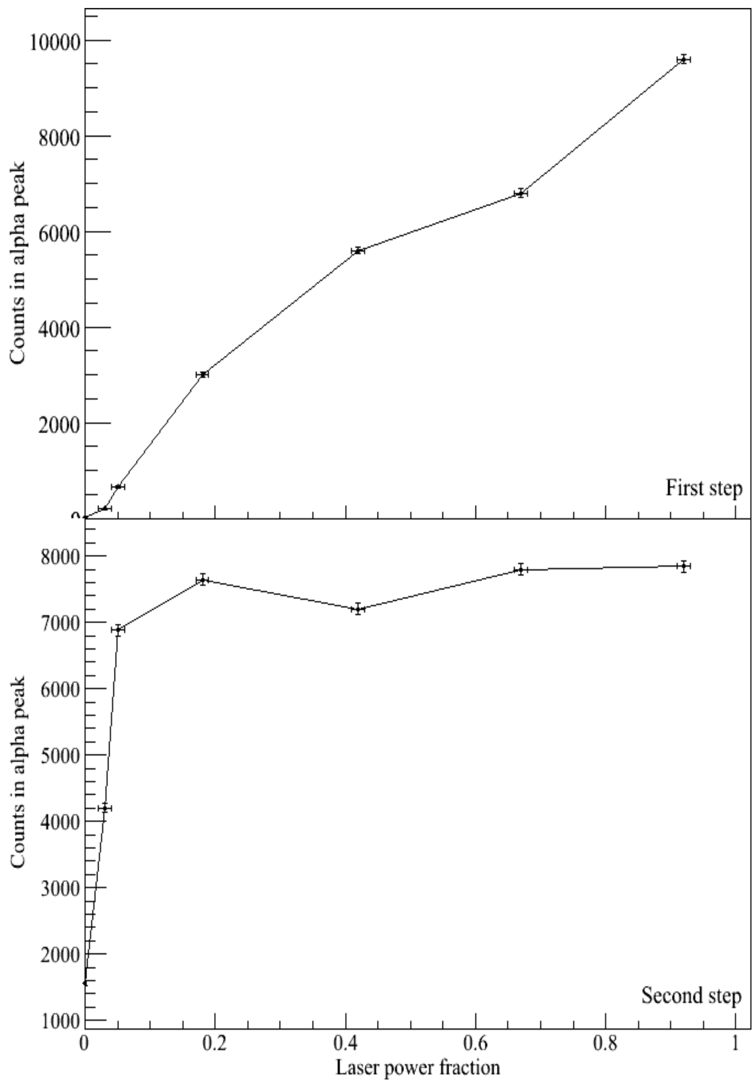


Isotope Shift

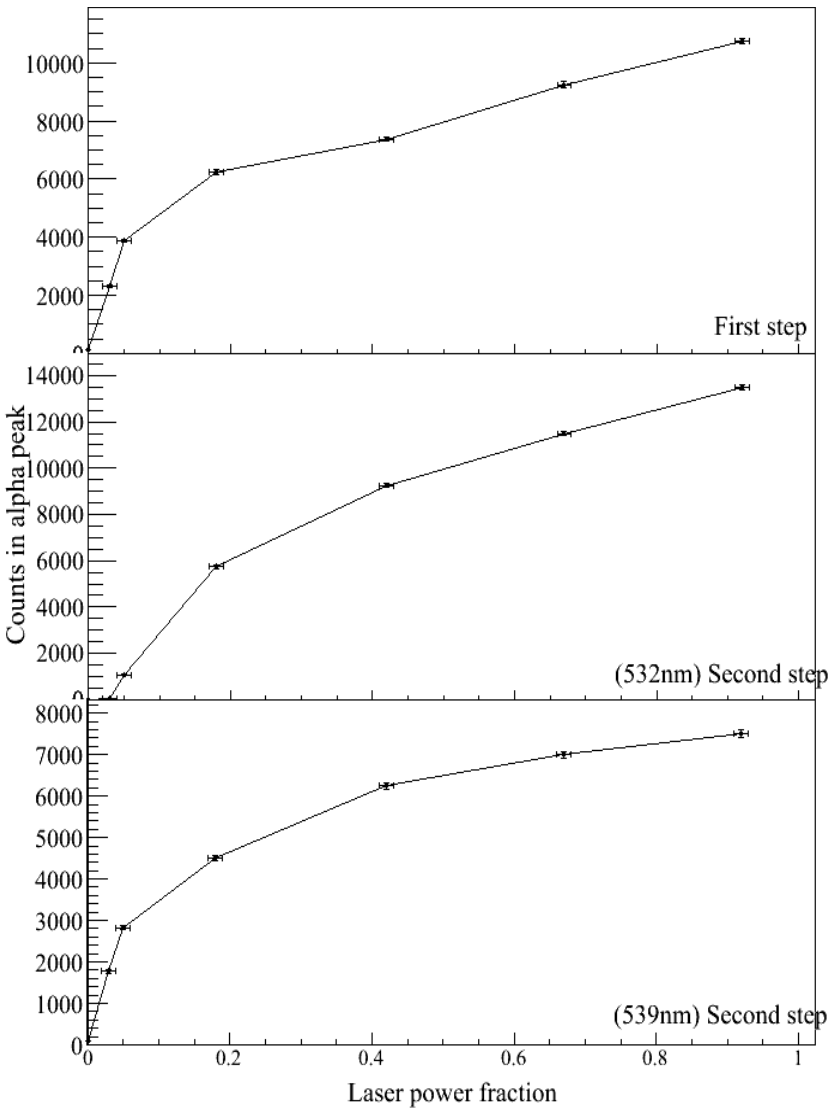


$$\Delta \nu \approx F \cdot \delta \langle r^2 \rangle + Mass\ Shift$$

Laser Saturation



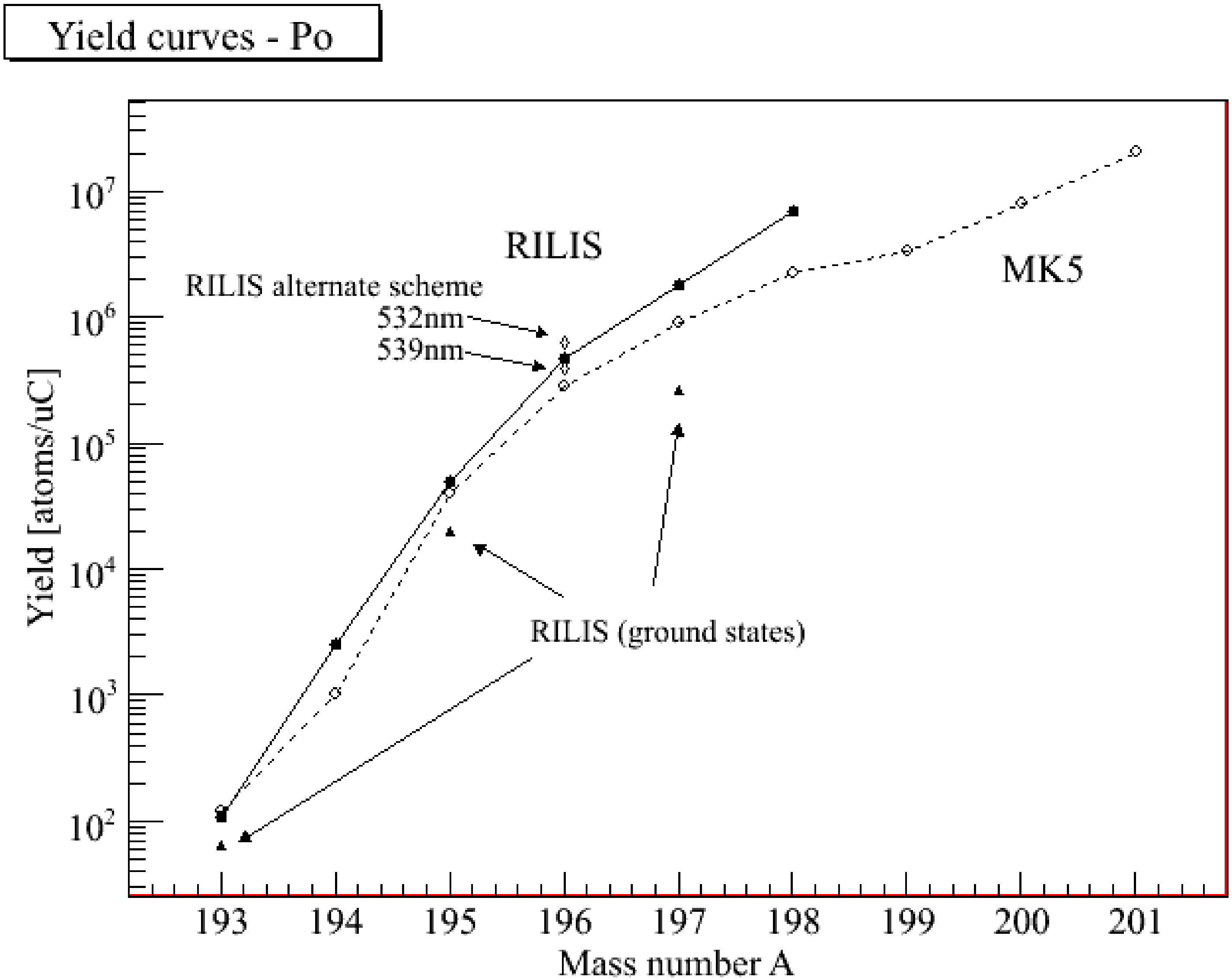
First scheme



Second scheme

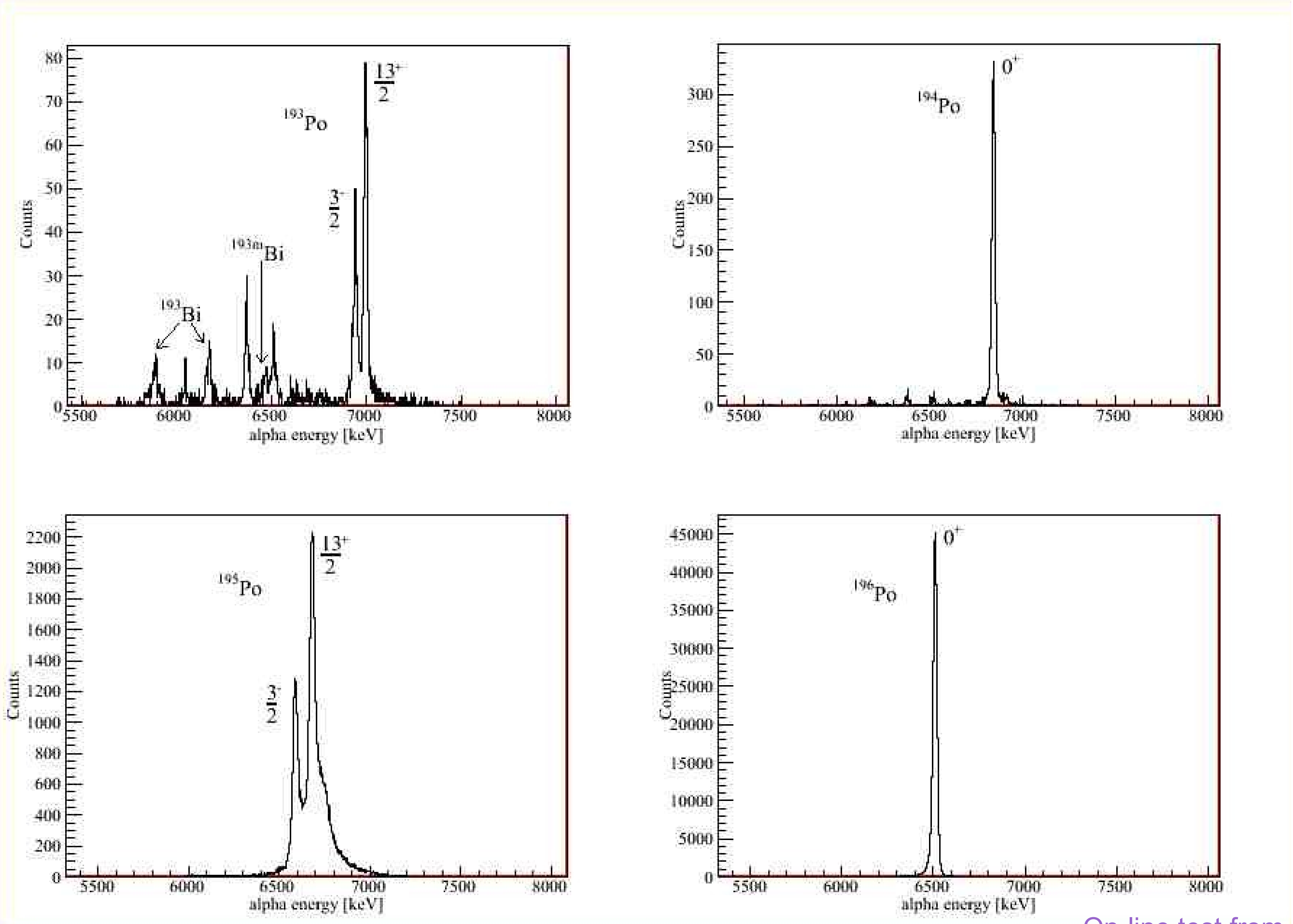
On-line test from Nov.2006

Po Yields



On-line test from Nov.2006

Po α Detection



On-line test from Nov.2006

Conclusions and Outlook

- The measurement of the $\delta\langle r^2\rangle$ of the polonium isotopes is required to understand to picture across the Z=82 shell gap.
- The new development of a laser ionization scheme at ISOLDE makes this possible via in-source laser spectroscopy.

- IS456: *19 shifts* for the study of the even-even isotopes.
- Odd-even isotopes and nuclear spectroscopy to follow.